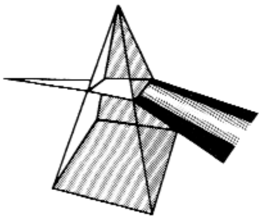
【技術報告】



計装系応答特性の供用中測定法の開発

上田 雅司　友部 勝眞[*]　瀬戸口啓一[*1]
遠藤 昭

敦賀本部 国際技術センター
＊ 敦賀本部 高速増殖炉もんじゅ建設所
＊1 敦賀本部 業務総括部

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Development of Methodology for In-service Measurement of Transient Response of Process Instrument used in LMFBR

Masashi UEDA　Katsuma TOMOBE[*]　Keiichi SETOGUCHI[*1]
Akira ENDOU
International Corporation and Technology Development Center, Tsuruga Head Office
＊ Monju Construction Office, Tsuruga Head Office
＊1 Administration Division, Tsuruga Head Office

熱電対などの検出器の応答特性は、使用条件に依存する。このため、実機使用条件下で行えるセンサ応答特性の測定法の開発を行った。測定対象物理量が、測定すべき検出系の応答より速い速度でゆらぐ場合、出力ゆらぎは系の応答を反映したものになる。したがって、検出系の出力ゆらぎに自己回帰（AR）モデルをあてはめることにより、モデルパラメータより系の応答特性を知ることができる。測定対象物理量の応答を検出系より速い応答で観測出来る場合には、入力を白色雑音と仮定するARモデルに比べ、より速い応答での観測値を外部入力としたARXモデルを用いるのが、より直接的で有用な方法である。

もんじゅ燃料集合体出口熱電対の出力ゆらぎに、ARモデルをあてはめて行った応答特性の測定結果は、より速い応答の渦電流温度計の出力を外部入力とするARXモデルによる測定結果と良く一致した。一次主冷却系電磁流量計(EMF)のゆらぎは、ARモデルによる応答特性の点推定を可能にする程速くはないが、EMFの応答はARモデルをあてはめて行った測定の結果より速いことが確かめられた。

As a sensor's response depends on the operating conditions such as thermo-hydraulics, it is desirable to develop a measuring method of the sensor response at as-installed operating conditions. In-service measuring methods were, therefore, developed for the sensor response time measurements. If the physical quantity to be measured has higher frequency fluctuation than the sensor's frequency response, the dynamics of sensor is reflected to the output fluctuation.

Then, the sensor response characteristic may be derived from the AR model parameters filled to the output fluctuations. The inclusion of the AR model with exogenous input (ARX model) is a straightforward method when the physical variable to be measured has a faster response than the sensor response. The subassembly outlet thermocouple response measured using the AR model agreed fairly well with that measured using the ARX model with the eddy-current thermometer output as the exogenous input. The electromagnetic-flowmeter (EMF) response time was estimated using the AR model only when the fluctuation of the flow rate was faster than the EMF response. However, it can be concluded that the EMF response is faster than the measured value by means of AR model.

キーワード
渦電流式温度計、渦電流式流速計、応答特性、ゆらぎ、ARモデル、ARXモデル、プロセス計装、センサ、熱電対、電磁流量計
Process Instrument, Thermocouple, Electromagnetic-flowmeter, Eddy Current Sensor, Response, AR Model, ARX Model, LMFBR

１. Introduction

In a reactor plant, coolant temperature and flow rate are amongst the most important parameters for plant protection, control and monitoring. Hence, it is necessary to verify that the instrumentation systems measuring these satisfy the design criteria of response as well as accuracy.

In the liquid-metal-cooled fast breeder reactors (LMFBRs), there is very widespread use of metal-sheathed mineral-insulated thermocouples installed into thermowells. In such usage of the thermocouples, a time delay of the temperature measurement is caused by heat capacities of the well, mineral-insulator and stainless-steel sheath, and their overall thermal resistance including thermocouple-to-well contact resistance. Thus, numerous studies have been done to evaluate the time delays.[1), 2)] At the early stage of development of coolant temperature measurement system for LMFBR, response of thermocouples in thermowells to a sudden change in temperature of the surrounding fluid was measured in test facilities. However, it is desired to measure transient response of the thermocouple after installation and under operating condition. This is because the response depends on operating conditions such as thermal-hydraulic and/or as-installed conditions. Hence, the loop-current step response method (LCSRM) was developed to measure the transient response of the thermocouple during operation.[3)] In the LCSRM, a thermocouple junction is heated with an electric current and the time dependence of cooling is analyzed to predict the transient response when the current is turned off. However, it was pointed that a secondary electromagnetic force (emf) was generated by the activating current, when the LCSRM was used for chromel/alumel thermocouples which are extensively used.

To avoid the secondary emf, it is preferable to adopt a passive method. A potential was shown for the use of auto-regressive modeling of sensor output signal fluctuation for on-line monitoring of the response time of the process sensors.[4)] The method of using AR model is an attractive one which requires observation of only output fluctuation from a sensor, provided that the sensor dynamics is reflected in the output fluctuation.

Concerning flow rate measurement, electromagnetic flowmeters (EMFs) have been extensively used in LMFBRs, because it is simple to ensure coolant boundary integrity and because of their stable and linear characteristics. Usually, direct-current excited saddle coil-type EMFs or permanent magnet-type EMFs are selected to overcome the skin effect due to high electric conductivity of the coolant in the EMF. The accuracy of the EMFs is verified with flow calibration in a test loop and/or with an analytical evaluation of the output characteristics before installation in a reactor plant.[5)] Methods of in-service calibration have also been developed to verify that the measurement accuracy is maintained during the reactor operation period[6)~9)].

On the other hand, the response time of the EMF has not been a matter of great concern, since the response of the EMF is relatively fast as compared with other sensors. However, in the design study of large-scale FBRs, it is thought that the response might become slower with the increase in the diameter of the pipe. Therefore, the need for a quantitative evaluation of the response was acknowledged. Thus, an equation describing the response characteristic of the EMF was derived using first principles to describe the electromagnetic process occurring inside the coolant flowing in the section of the pipe in the EMF.[10)] A direct measurement of the EMF response can complement the theoretical analysis. However, it is not realistic to make response time measurement of large scale EMFs in a test facility, because it requires very large scale equipment.

The above-mentioned are the reasons why it is desired to develop methods for in-service sensor response measurement. Fluctuations in sensor output signal can provide information about the sensor dynamics, a clue related to the sensor response may be obtained from these. A method to extract such information is by AR model-fitting of the fluctuations of the sensor output signals.[11)] The method of using AR model is applicable when the physical process causing the output fluctuation constitutes an auto-regressive process. In the use of AR model, it is necessary to observe only the sensor output fluctuation. An AR model with exogenous input (ARX model) can also be used to measure sensor transient response when the physical variables to be sensed can be observed alternatively with a much faster response than the sensor response.

In applying AR model to measurement of sensor response it is necessary to check that the physical quantity to be sensed has sufficiently higher frequency fluctuations than the sensor's frequency response limit, or the sensor output fluctuation is caused by an auto-regressive process. Thus, an experiment was conducted to examine the applicability of using AR model and ARX model to the measurement of transient response of the fuel assembly outlet coolant thermometers and the primary loop EMF of Monju, the prototype fast breeder reactor in Japan. In this paper, the results of the experiment are evaluated.

2. Theoretical Background[12),13)]

For completeness, a brief description is given for the theoretical results of the AR and ARX modelings which are used in measurement of the transient response.

(1) AR Model Fitting

A stationary time series x_i acquired from discrete sampling of a sensor output fluctuation $x(t)$, with a sampling time interval Δt, can be modeled as output of a linear system with white noise input, e_i, by using an auto-regression process as shown in Fig.1:

$$x_i = \sum_{m=1}^{M} a_m x_{i-m} + e_i \qquad \cdots\cdots ?$$

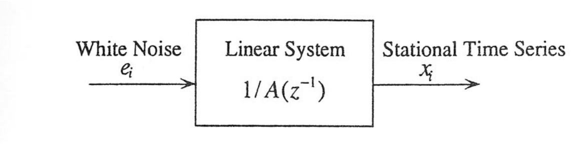


Fig.1 AR Model

Transient response of the linear system can be derived from the model parameters, a_m of the above equation. Derivation of the transient response is obtained by use of the solution for linear optimal estimation as follows :

Let us consider the residual series, e_i (i=1,2,...)which is obtained by subtracting the predicted value, $\hat{x}_i$ of & using AR model from the measured value, x_i :

$$\begin{aligned} e_i &= x_i - \hat{x}_i \\ &= x_i - \sum_{m=1}^{M} a_m^{(M)} x_{i-m} \end{aligned} \qquad \cdots\cdots(2)$$

The model parameters $a_m^{(M)}$ (m=1,2,...,M) are determined so as to minimize the mean square value of e_i, $J=E[e_i^2]$ Then, it is necessary for $a_m^{(M)}$ to satisfy

$$R_{0k} - \sum_{m=1}^{M} a_m R_{km} = 0, \quad k = 1,2...,M$$

$$R_{km} = \frac{1}{M} \sum_{i=1}^{M} x_{i-m} x_{i-k} \qquad \cdots\cdots(3)$$

from the condition of $\partial J / \partial a_m^{(M)}$ for m=1,2,...M. By using matrix notation, the solution is expressed by

$$\alpha = R^{-1} r \qquad \cdots\cdots(4)$$

where

$$\alpha^T = \left[a_1^{(M)}, a_2^{(M)}, ...a_m^{(M)}, ...a_M^{(M)} \right]$$

$$R = \frac{1}{M} \sum_{i=1}^{M} XX^T$$

$$r^T = \left[R_{01}, R_{02}, ...R_{om}, R_{0M} \right] = \frac{1}{M} \sum_{i=1}^{M} x_i X^T$$

$$X^T = \left[x_{i-1}, x_{i-2}, ...x_{i-m}, x_{i-M} \right] \qquad \cdots\cdots(5)$$

The model order M is determined by use of Akaike's AIC criterion.Introducing the time lag operator, z^{-1}, to eq.(2) leads to

$$\begin{aligned} x_i &= e_i \Big/ \left(1 - \sum_{m=1}^{M} a_m^{(M)} z^{-m} \right) \\ &= e_i / A\left(z^{-1}\right) \end{aligned} \qquad \cdots\cdots(6)$$

This equation means that x_i is the output of the linear system having a transfer function, $1/A(z^{-1})$ with the white noise input, e_i. Hence, the impulse response series is obtained as

$$\sum_{n=0}^{\infty} h(n\Delta t) z^{-n} = 1/A\left(z^{-1}\right) \qquad \cdots\cdots(7)$$

Consequently we obtain the step response function :

$$S(m\Delta t) = \sum_{n \le m} h(n\Delta t)\Delta t \qquad \cdots\cdots(8)$$

(2) ARX model

The ARX model is an extension of the AR model with a structure as shown in Fig.2. Taking account of the exogenous input u_i(i=1,2,...N) into consideration, the output is modeled as:

$$x_i = \sum_{m=1}^{M} a_m x_{i-m} + \sum_{n=1}^{N} b_n u_{i-n} + e_i \qquad \cdots\cdots(9)$$

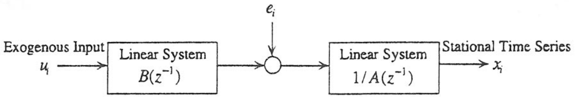


Fig.2 ARX Model

The model parameters a_m, b_n are calculated by

$$\alpha = R^{-1} r \qquad \cdots\cdots(10)$$

for

$$\alpha^T = \left[a_1, a_2, ...a_M, b_1, b_2, ...b_N \right]$$

$$R = \frac{1}{M+N} \sum_{i=1}^{M+N} XX^T$$

$$r = \frac{1}{M+N}\sum_{i=1}^{M+N} x_i X^T$$

$$X^T = \left[x_{i-1}, x_{i-2}, ...x_{i-M}, u_{i-1}, u_{i-2}, ...u_{i-N}\right] \quad \cdots\cdots(11)$$

Then, the output x_i is expressed by

$$x_i = \frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}u_i + \frac{1}{A\left(z^{-1}\right)}e_i \quad \cdots\cdots(12)$$

for

$$A\left(z^{-1}\right) = 1 - \sum_{m=1}^{M} a_m z^{-m}$$

$$B\left(z^{-1}\right) = 1 - \sum_{n=1}^{N} b_n z^{-n} \quad \cdots\cdots(13)$$

Therefore, the impulse response series and the step response function are obtained as follows:

$$\sum_{n=0}^{\infty} h(n\Delta t)z^{-n} = B\left(z^{-1}\right)/A\left(z^{-1}\right)$$

$$S(m\Delta t) = \sum_{n\leq m} h(n\Delta t)\Delta t \quad \cdots\cdots(14)$$

3. Sensor Location and Instrumentation System

The plant system configuration and sensor locations of Monju are shown in Fig.3. Applicability of AR model fitting to the measurement of transient response is examined for the fuel subassembly outlet coolant thermometers and the EMF that measure primary coolant flow rate. Those sensors being studied are double circled in Fig.3.

(1) Fuel Subassembly Outlet Coolant Thermometer

A thermocouple is installed at the outlet of every fuel subassembly to measure the fuel outlet coolant temperature. Some of the subassemblies are also equipped with a eddy-current flow probe (ECFP) as shown in Fig.4. The ECFP is installed primarily to sense flow velocity at the S/A outlet to make sure appropriate flow distribution across the core region of the reactor, but temperature signal can also be measured with extremely fast response compared to the thermocouple. The basic principle of the ECFP is illustrated in Fig.5$^{14)}$. The ECFP consists of a central primary coil energized by an alternating current and two identical secondary coils flanked symmetrically at both sides of the primary. A magnetic field produced by the central primary coil penetrates the sodium near the ends of the coil. The radial component of the magnetic

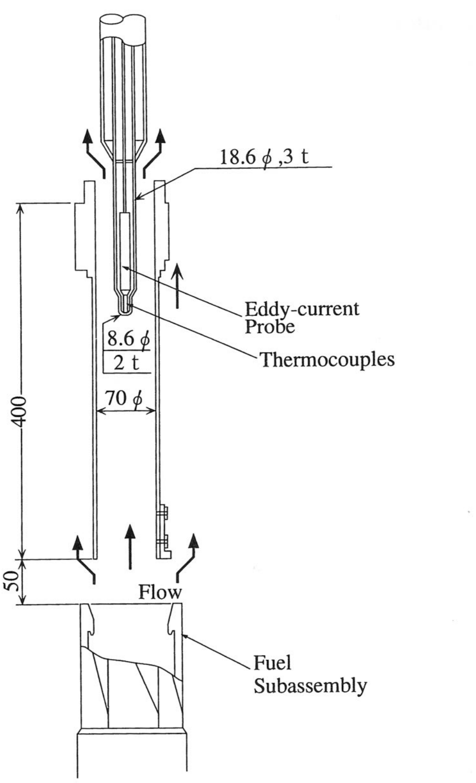


Fig.4 Configuration of Eddy-current Flow Probe

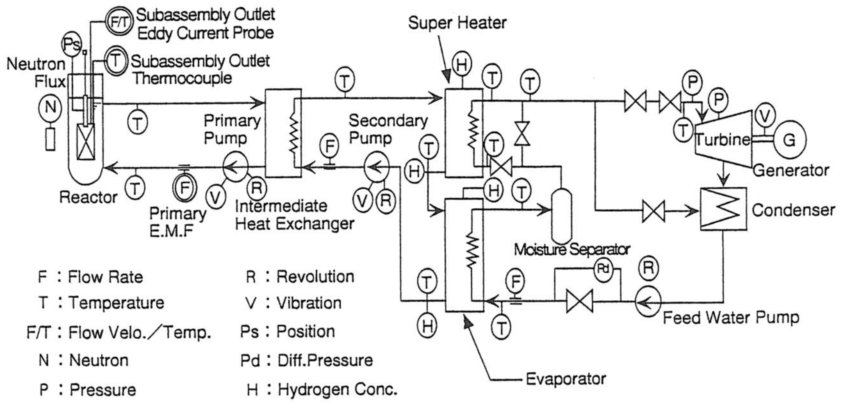
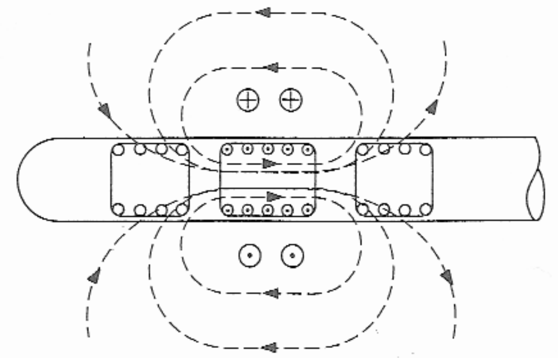
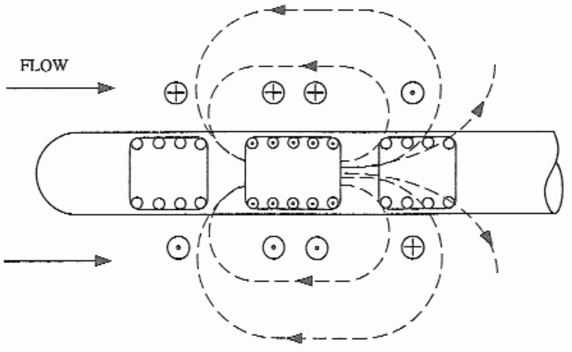


Fig.3 System Configuration and Sensor Location of Monju



(a) Static Sodium



(b) Flowing Sodium

Fig.5 Principle of Eddy-current Flow Probe

Table.1 Specification of EMF Used in Transient Response Measurement

Type	Permanent magnet type
Fluid	Liquid sodium
Measuring range	0 to 7,800 m^3/h
Output voltage	10 mV/5,970 m^3/h
Operating temperature	397°C
Pipe size	22B(590.6-mm inside diameter)
Aspect ratio	2.5

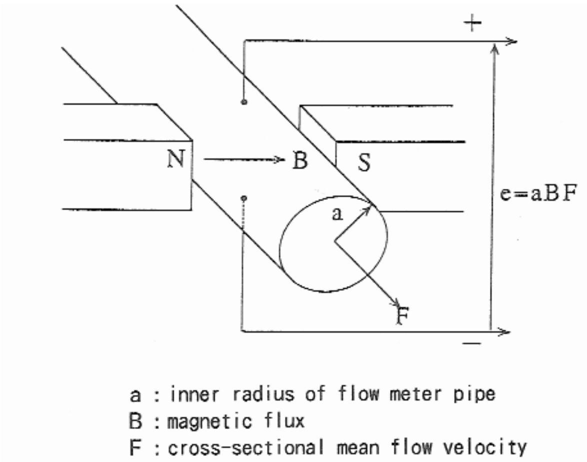


Fig.6 Schema of Permanent Magnet type EMF

field interacts with the flowing sodium to induce circulating electric currents, *i.e.*, eddy-currents, which in turn produce their own magnetic fields.

The eddy-currents distort the applied field by the primary coil so as to be pulled down-stream. The two secondary coils when connected differentially sense this field distortion which depends on the sodium flow velocity. On the other hand, the two secondary coils when connected summationally cancel the distortion effects and sense the magnitude of the induced eddy-current which depends on only the sodium temperature. Thus, we can also get information about the sodium temperature from the output of the ECFP. Hereafter, we call the temperature signal from the ECFP as the eddy-current thermometer output.

In the subsequent chapter, applicability of an ARX model with the eddy-current thermometer output as the exogenous input is examined for the measurement response of the fuel subassembly outlet thermocouple.

⑵ EMF for Primary Cooling System

A permanent magnet type EMF is installed in the cold leg piping of each loop in the primary cooling system of Monju. The specification of the EMF is shown in Table 1. The EMF has a relatively simple structure as shown in Fig.6, in which the magnet is fixed so that its axis is at right angle with that of the pipe and electrodes are directly welded on the outer surface of the pipe so as to be perpendicular to both the pipe and the magnetic field.

4. Measurement Result and Discussion

The transient response measurement of the subassembly outlet thermocouple was conducted by means of both ARX model fitting and AR model fitting. Also, applicability of the AR model fitting to in-service measurement is examined for the eddy-current thermometer and the EMF for the primary coolant flow rate of the reactor.

⑴ Subassembly Outlet Thermocouple

When the variation of temperature to be sensed can be observed by an alternate means faster than the response of the sensor and the eddy current thermometer is installed at a position very close to the thermo couple as shown in Fig.4, the ARX model fitting process using the observed temperature variation as the exogenous input is a straight forward and useful method to measure the sensor response. As the eddy-current thermometer response is expected to be considerably faster than the thermocouple response, it is planned to measure the thermocouple response by means of ARX modeling with the eddy-current thermometer output variation as the exogenous input. Thus, the thermocouple and eddy-current thermometer output signals was acquired in operation at 38% of the rated reactor power, superposed with a, ±2% pseudo random power variation in the manner of a M-sequence. The acquired output signals are shown in Fig.7. The measured transient response by ARX model filling process is shown in Fig.8. It is clear from the measurement result that the response time of the thermocouple which reaches 63.2% of the settling value is 9.4sec.

The transient response is also measured as shown in Fig.8 by means of AR model fitting to the thermocouple output fluctuation observed during stationary operation at 43% of the rated reactor power. The measured response time is 9.6sec. The results by ARX and AR models agreed fairly well with each other and also agreed with the result measured by means of step change in sodium temperature conducted at a test facility.

In order for AR model to be applicable to measurement of sensor transient response, it is necessary that the physical quantity to be sensed has sufficiently higher frequency fluctuations than the sensor's frequency response limit. To examine the applicability of AR model fitting to in-service measurement of the fuel subassembly outlet thermocouple, observation and spectral analysis were made for the fluctuations involved in the thermocouple and eddy-current thermometer outputs. The observed fluctuation wave forms and measured auto-power spectrum density are shown in Fig.9 and Fig.10, respectively. It is seen from these results that the temperature fluctuation measured by the fast responding eddy-current thermometer involves relatively higher frequency components and has a considerably widen spread frequency band as compared with the thermocouple

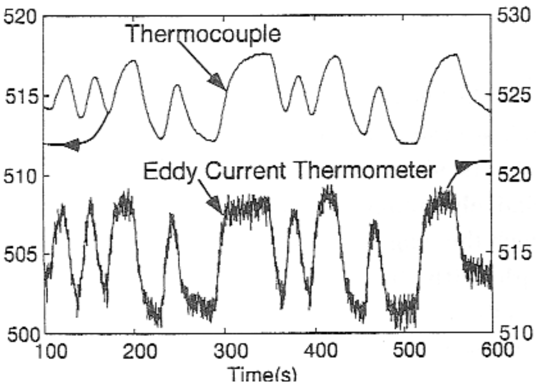


Fig.7 Variation Observed with Thermocouple and Eddy-Current Thermometer Output

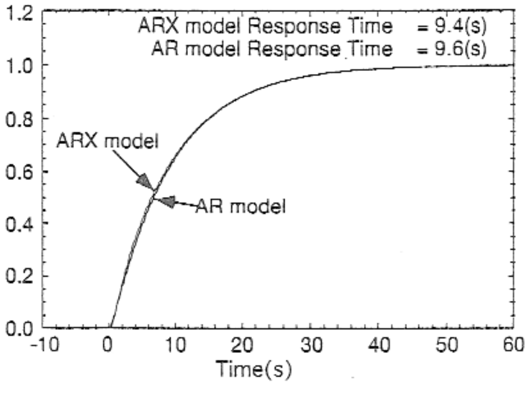


Fig.8 Measured Response of Fuel Subassembly Outlet Thermocouple

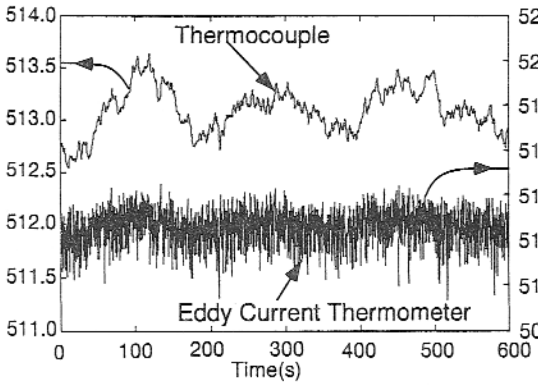


Fig.9 Fluctuation observed with Thermocouple and Eddy-Current Thermometer Output

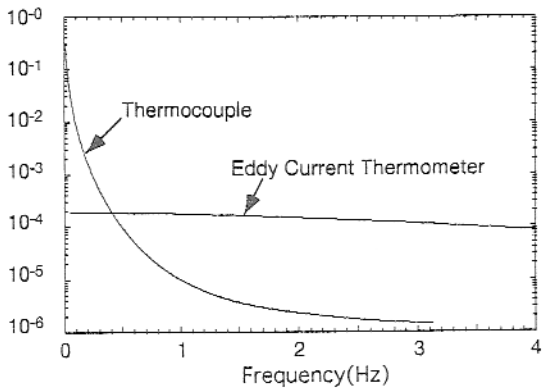


Fig.10 Power Spectrum Density of Thermocouple and Eddy-Current Thermometer Output Fluctuations

output fluctuation. This means that the thermocouple dynamics is reflected in the sensor output and the frequency band of the output fluctuation is limited by the frequency response characteristic of the thermocouple with the input temperature fluctuation having higher frequency components. Hence, it is judged that the AR model fitting is applicable to in-service response measurement of the thermocouple for the subassembly outlet coolant temperature. Thus, we have means to measure transient response of the subassembly outlet thermocouple, even for those subassemblies not equipped with eddy-current thermometers.

(2) Eddy-current Flowmeter / Thermometer

Responses of the eddy-current flowmeter and thermometer were measured using the AR model. The results are shown in Fig.11. It is seen from Fig.11 that the response time of the flowmeter and thermometer agree with each other and are approximately 70ms. Since the frequency band of the electronics connected to the eddy-current flowmeter/thermometer probe is limited from DC to about 10 Hz in the sense of a -3dB power reduction, it seems that the response time of 70ms is dominated by the electronics and the response time of the flowmeter/thermometer is shorter than 70ms. It was also observed that the power spectrum density extended smoothly to the band limit of the electronics. Therefore, we can measure the response of the eddy-current flowmeter/ thermometer for the fuel subassembly outlet coolant by use of the AR model fitting.

(3) EMF for Primary Cooling System

The EMF transient response was estimated using the AR model as shown in Fig.12. The estimated response time decreased with increasing flow rate and reached about 110ms at the rated condition as shown in Fig.13. As the estimated response time continued to diminish even when reaching the rated flow, it is suspected that the fluctuation frequencies of the flow velocity, even at the rated condition, are lower than the EMF frequency response limit. Only when the fluctuations of the flow velocity are faster than the EMF response time, will the latter be correctly estimated. However, it can be concluded from the measurement result that the EMF response is faster than 110ms.

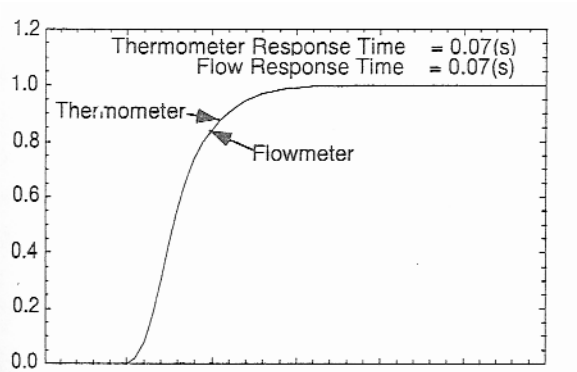


Fig.11 Measured Response of Subassembly Outlet Eddy-current Flow/Thermometer

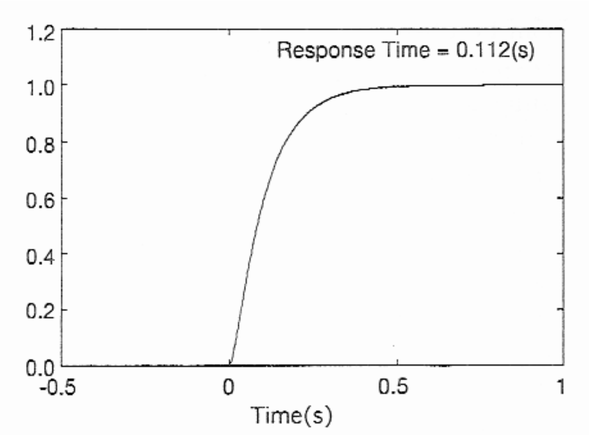


Fig.12 Estimated Response of EMF

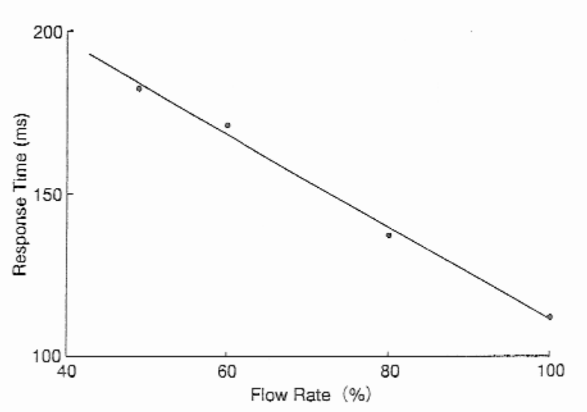


Fig.13 Dependence of EMF Response Time on Flow

5. Conclusion

Applicability of the ARX and AR model fitting processes to in-service measurement of sensor transient response has been examined for the subassembly outlet thermometers and EMF for primary coolant flow rate of Monju. The major conclusions from the examination are as follows:

(1)The ARX model fitting is a straight forward method when the physical variable to be sensed can be observed alternatively with a faster response than the sensor response. The subassembly outlet thermocouple response could be measured using the ARX model with the eddy-current thermometer output as the exogenous input.

⑵The coolant temperature fluctuations at the subassembly outlet have sufficiently widespread frequency bandwidth which allows the measurement of the transient response of the thermometer by means of AR model fitting. The transient responses of the subassembly outlet thermocouple and eddy-current thermometer could be measured by means of AR model fitting.

⑶The measured transient responses by ARX and AR models agreed fairly well with each other and also agreed with the result measured by means of step change in sodium temperature conducted at a test facility.

⑷The primary EMF response time was estimated using the AR model at different flow conditions. The estimated value decreased with increasing flow rate. As the estimated response time continued to diminish even when reaching the rated flow, it is suspected that the flow fluctuation frequencies, even at the rated condition, are lower than the EMF frequency response limit. Only when the flow fluctuations are faster than the EMF response, will the latter be correctly estimated. However, it can be concluded from the measurement result that the EMF response is faster than estimated at the rated flow condition.

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